

# **Light Ion EDM Search with a Magnetic Storage Ring**

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# Introduction

EDMs, CP/T violation and measurement overview

# *Dipole Moments in a Nut Shell*

The electric and magnetic dipole moments are a measure of the directional interaction between a particle and an electro-magnetic field:

$$\mathcal{H} = - \left( \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E} \right) \quad \vec{\tau} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

‘Zeeman/Hyperfine’                                    ‘NMR’

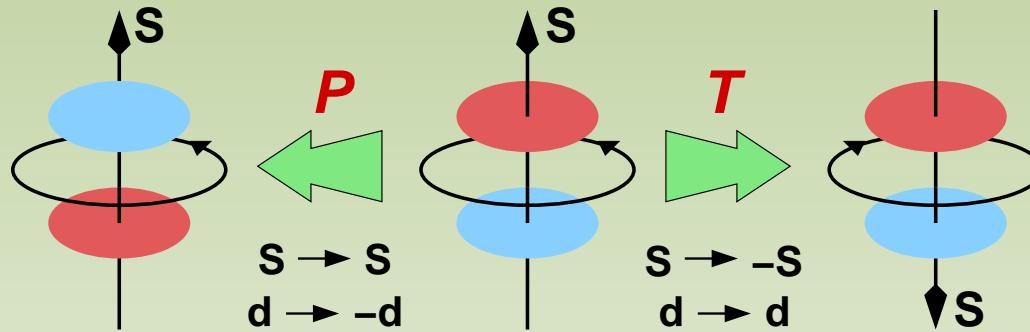
Dipole moments are aligned along the spin.

$$\vec{\mu} = g \frac{e \hbar}{2 m c} \vec{S} \quad \vec{d} = \eta \frac{e \hbar}{4 m c} \vec{S}$$

Can be related to each other as the real and imaginary part of a more general dipole moment  $\vec{D}$ .

# *EDMs Break P and T*

Elementary particle can only have a permanent electric dipole moment if both **parity** and **time reversal** symmetries are broken:



the Standard Model predicts **EDMs** to be (practically) **zero**

**SO**

**Any EDM found by a planned or proposed search  
would be a signal of physics beyond the SM!**

# *How does a storage ring help?*

## Discovery Phase

a larger effective electric field from  $\vec{v} \times \vec{B}$  in particle frame

increase is 10 to 100 times typical laboratory field

the ability to extend searches to charged particles

muon, deuteron, proton, ( ${}^3\text{H}$ ,  ${}^3\text{He}$ ,  $\dots$ )

## Exploration Phase

different systematic effects from trap or box searches

not subject to leakage current

comparison of related systems (proton, neutron, deuteron)

allow initial exploration of source of CP-violation

EDM on quark or in N-N interaction

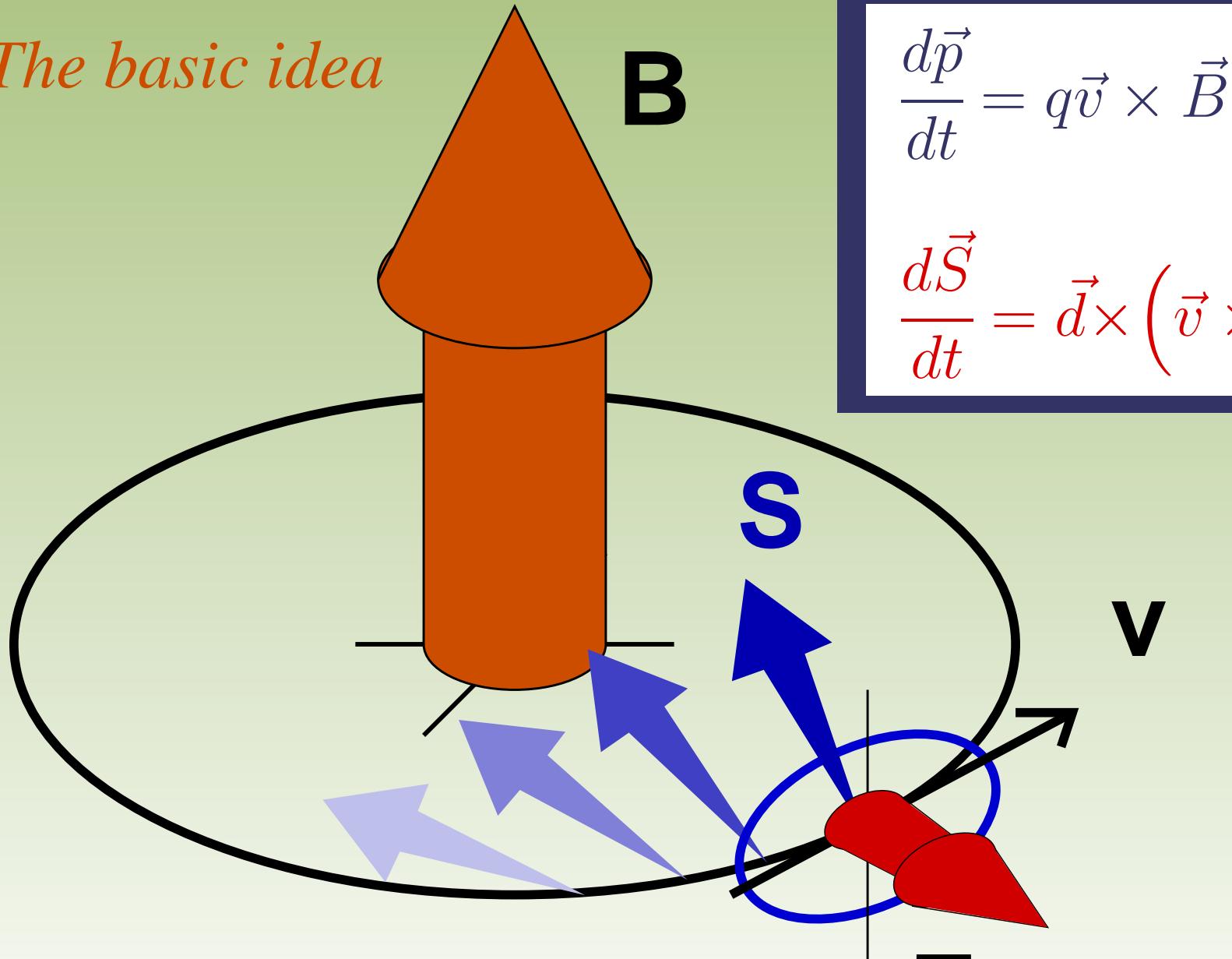
permit special sensitivity to quark EDMs in deuteron case

Liu & Timmermans, PRC 70, 055501 (2004), Lebedev *et al.*, PRD 70, 016003 (2004)

# Storage Rings

Several techniques to measure EDMs of charged particles

*The basic idea*



$$\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$$

$$\frac{d\vec{S}}{dt} = \vec{d} \times (\vec{v} \times \vec{B})$$

$\vec{E}^* = \vec{v} \times \vec{B}$  can be very large (GV/m)

$$E = v \times B$$

# *Spin precession for relativistic particle*

$$\vec{\omega} = a \vec{B} + \left( a - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \vec{E} \right)$$

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**For  $E = 0, B = B_z$ :**

(1)  $\omega = \sqrt{a^2 + (\eta \beta)^2 / 4} B$

(2)  $\vec{\omega} \times \vec{B} \neq 0 \Rightarrow \phi \simeq \eta \beta / 2a$

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**For  $E_r \simeq a B c \beta \gamma^2, B = B_z$ :**

(3)  $\vec{\omega} = \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \vec{E} \right)$

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**For  $\mathbf{E}_r \simeq \mathbf{a} \mathbf{B} \propto \beta \gamma^2, \mathbf{B} = \mathbf{B}_z$ :**

(3)  $\vec{\omega} = \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \vec{E} \right)$

**For  $\mathbf{E}(t) = \mathbf{E}_s \cos(\omega_L t), \mathbf{B} = \mathbf{B}_z$ :**

(4)  $\langle \omega_r \rangle = \eta \Delta \beta \mathbf{B} / 4 \cos(\phi)$

# Parasitic

Only completed EDM experiment using a storage ring

# *The ‘parasitic’ way*

From  $\omega = \sqrt{a^2 + (\eta\beta/2)^2}B$ :

need to know  $a$  precisely

⇒ only leptons

⇒ large model sensitivity

From tilt in  $\vec{\omega}$ :  $\phi \simeq \eta\beta/2a$

large systematic from geometry

For both:

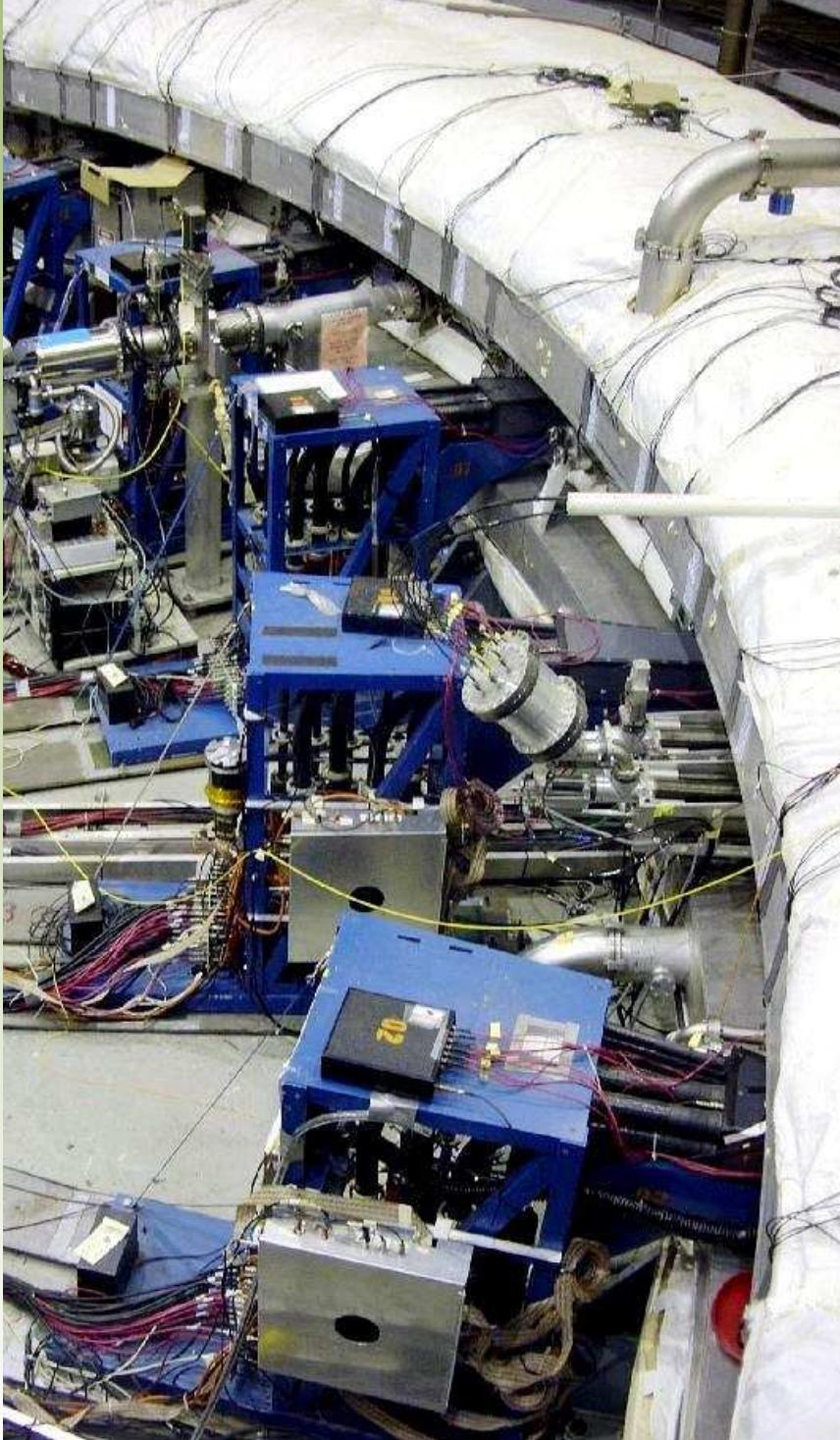
sensitivity  $\propto \beta$

⇒ no traps ....

$$\|d_\mu\| < 2.8 \times 10^{-19} \text{ e} \cdot \text{cm} = 10^{16} \times d_\mu^{SM}$$

J. Bailey *et al.*, J. Phys. G : Nucl. Phys., Vol. 4, No. 3, 1978.

R. McNabb, <http://www.arxiv.org/abs/hep-ex/0407008>.



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# Frozen Spin

Good when anomalous magnetic momement is small: muon

# The ‘frozen spin’ way

$$\text{EDM} \propto dS_z/dt$$

Use electric field to make  $\omega_a = 0$

$$E_r = \frac{a B_z c \beta}{1 - (1 + a) \beta^2}$$

EDM induced precession rate:

$$\vec{\omega}_\eta = \frac{\eta}{2} \left( \vec{\beta} \times \vec{B}_z + \vec{E}_r \right)$$

Effective electric field:

$$\xi = \frac{\beta B_z + E_r}{E_r} = \frac{a + 1}{a \gamma^2}$$

$$d\text{EDM} \propto \frac{1}{\sqrt{\mathcal{N}} P_\circ A \xi E_r \sqrt{\tau \tau_p}}$$

	$\mu$	${}^2\text{H}$	
a	0.001	-0.143	
p	0.5	0.7	GeV/c
$\gamma$	5	1.06	
$\xi$	34	-5.5	
E	2	3.5	MV/m
B	0.25	0.21	T
$\rho$	7	13	m
$\tau$	$10^{-5}$	10	s
$\sigma_d^\dagger$	$10^{-24}$	$10^{-27}$	e · cm

$^\dagger$  for  $N = 10^{16}$

F.J.M. Farley *et al.*, A new method of measuring electric dipole moments in storage rings, Phys.Rev.Lett. 93 (2004) 052001

Y.K. Semertzidis *et al.*, A New Method For A Sensitive Deuteron EDM Experiment, <http://www.arxiv.org/abs/hep-ex/0308063>

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# *Particles and Nuclei with small a*

**leptons:**  $\mu$

**$\beta$ -emitters** (from I.B. Khriplovich):

$^{24}_{11}\text{Na}$ ,  $^{60}_{27}\text{Co}$ ,  $^{82}_{35}\text{Br}$ ,  $^{94}_{37}\text{Rb}$ ,  $^{110}_{47}\text{Ag}^*$ ,  $^{118}_{49}\text{In}^*$ ,  $^{120}_{49}\text{In}^*$ ,  $^{121}_{50}\text{Sn}$ ,  $^{125}_{51}\text{Sb}$ ,  $^{131}_{53}\text{I}$ ,  
 $^{133}_{53}\text{I}$ ,  $^{133}_{54}\text{Xe}$ ,  $^{134}_{55}\text{Cs}$ ,  $^{136}_{55}\text{Cs}$ ,  $^{137}_{55}\text{Cs}$ ,  $^{139}_{55}\text{Cs}$ ,  $^{141}_{55}\text{Cs}$ ,  $^{143}_{55}\text{Cs}$ ,  $^{140}_{57}\text{La}$ ,  $^{160}_{65}\text{Tb}$ ,  
 $^{170}_{69}\text{Tm}$ ,  $^{177}_{71}\text{Lu}$ ,  $^{183}_{73}\text{Ta}$ ,  $^{196}_{79}\text{Au}$ ,  $^{198}_{79}\text{Au}$ ,  $^{203}_{80}\text{Hg}$ ,  $^{222}_{87}\text{Fr}$ ,  $^{223}_{87}\text{Fr}$ ,  $^{224}_{87}\text{Fr}$ ,  $^{242}_{95}\text{Am}$

**Stable isotopes** (from K. Jungmann):

$^2_1\text{H}$ ,  $^6_3\text{Li}$ ,  $^{75}_{33}\text{As}$ ,  $^{123}_{51}\text{Sb}$ ,  $^{139}_{57}\text{La}$ ,  $^{171}_{70}\text{Yb}$

A technique with a lot of potential!!

# Resonance

Well suited for a broad class of charged particles: deuteron

# *A closer look at spin dynamics*

The equation of motion for the in-plane spin component (MDM):

$$\frac{d\vec{S}_{xy}}{dt} \simeq a \left( \vec{S}_{xy} \times \vec{B} \right) \quad S_x = S_0 \cos(\omega t + \phi)$$

and for the out-of-plane component (EDM):

$$\frac{d\vec{S}_z}{dt} \simeq \frac{\eta}{2} \left( \vec{S}_0 \times (\vec{v} \times \vec{B}) \right) = -\frac{\eta}{2} S_x v_x B_z \hat{z}$$

Continuous growth of  $S_z$  if  $\langle S_x v_x \rangle \neq 0$

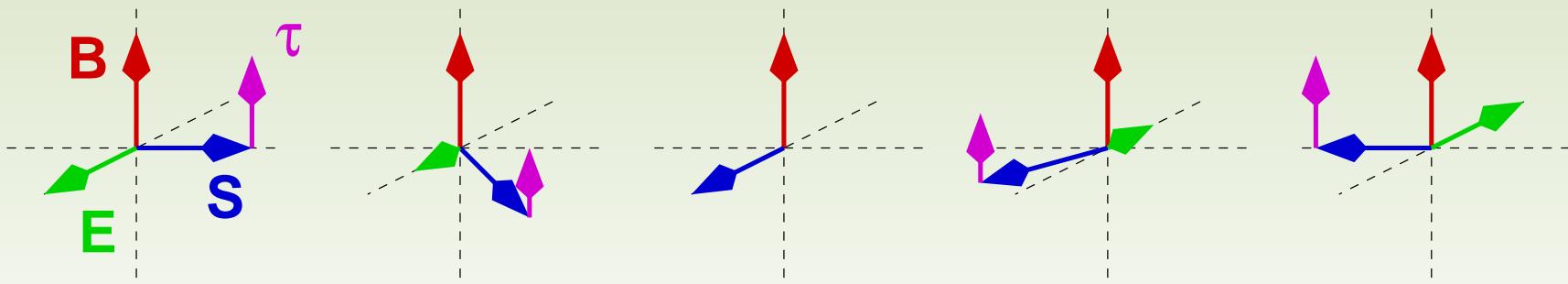
# *The ‘resonant’ way*

Modulate the velocity and create a resonance:

$$S_x v_x = S_0 \cos(\omega t + \phi) \times (v_0 + dv \cos(\Omega t + \Phi))$$

for  $\omega = \Omega$ ,  $\phi = \Phi$ :

$$\left\langle \frac{d S_z}{dt} \right\rangle = -\frac{1}{4} \eta S_0 dv$$



c.f. Rabi oscillatory fields, but in the particle rest frame!!

# Ring design

## Some Parameters:

Deuteron design

$T = 125 \text{ MeV}$

$p = 700 \text{ MeV/c}$

$B = 2 \text{ T}$

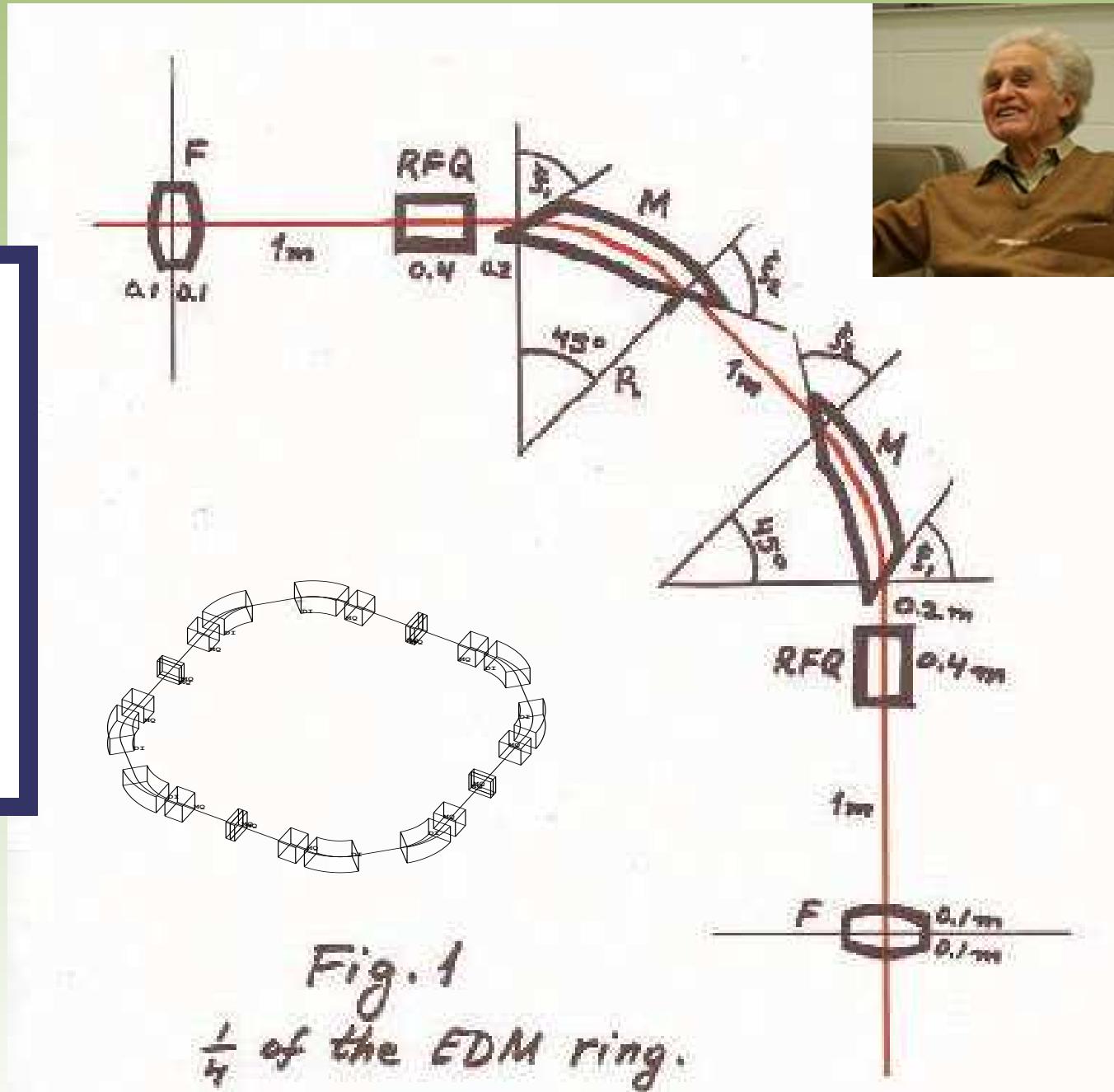
Circumference  $\sim 25 \text{ m}$

Synchrotron tune

$$Q_L = a\gamma = 0.154$$

Spin coherence time  
 $\sim 100 \text{ s}$

Acceptance  $\sim 10^{11} \text{ cm}^2 \text{H}$



# *Key Features of Resonance Method*

## No Radial Electric Field

⇒ Eliminates main systematic error of ‘frozen spin’ method

## Allows High Magnetic Field

⇒ much smaller ring, reduce cost

## Rapid Spin Precession

⇒ Eliminates whole class of ‘zero’ frequency systematic errors

## Resonances for $a\gamma - Q_L = 0, 1, 2, \dots$

⇒  $p$ ,  $^2\text{H}$ ,  $^3\text{H}$ ,  $^3\text{He}$  doable

Systematics still under study; no problems yet ...

$$\|\tilde{\mathbf{d}}\| \sim 10^{-29} \text{ e} \cdot \text{cm reachable}$$

# Conclusions

Excellent opportunities are presenting themselves ....

## *Summary and Conclusion*

Special storage rings offer the opportunity to search for an EDM on a charge particle at sensitivities extending down to  $10^{-29} \text{ e} \cdot \text{cm}$ (statistical for  $\sim 5$  months of data taking).

Observation of EDM at this level is a clear indication of physics beyond the Standard Model. An upper limit at this level would severely constrain SUSY models.

If an EDM were found, the storage ring provides an opportunity to search on more cases, allowing to investigate the source of CP-violation

The storage ring is challenging, but within reach of present technology.

# *The Storage Ring EDM Collaboration*

M. Aoki<sup>16</sup>, M. Bai<sup>5</sup>, G. Bennett<sup>5</sup>, A. Bravar<sup>5</sup>, H.N. Brown<sup>5</sup>, G. Cantatore<sup>17</sup>, A. Caracappa<sup>5</sup>, R.M. Carey<sup>3</sup>, P.T. Debevec<sup>9</sup>, H. Denizli<sup>1</sup>, P.D. Eversheim<sup>4</sup>, F.J.M. Farley<sup>5</sup>, C. Guclu<sup>11</sup>, R. Hackenburg<sup>5</sup>, S. Hoblit<sup>5</sup>, H. Huang<sup>5</sup>, K.P. Jungmann<sup>8</sup>, M. Karuza<sup>17</sup>, D. Kawall<sup>13,14</sup>, B. Khazin<sup>6</sup>, I.B. Khriplovich<sup>6</sup>, B. Kirk<sup>5</sup>, I.A. Koop<sup>6</sup>, Y. Kuno<sup>16</sup>, R. Larsen<sup>5</sup>, D.M. Lazarus<sup>5</sup>, L.B. Leipuner<sup>5</sup>, C.P. Liu<sup>8</sup>, V. Logashenko<sup>3,6</sup>, M. Lowry<sup>5</sup>, W.W. MacKay<sup>5</sup>, K.R. Lynch<sup>3</sup>, W. Marciano<sup>5</sup>, W. Meng<sup>5</sup>, J.G. Messchendorp<sup>8</sup>, L. Miceli<sup>5</sup>, J.P. Miller<sup>3,\*</sup>, W.M. Morse<sup>5</sup>, G. Noid<sup>10</sup>, C.J.G. Onderwater<sup>8</sup>, Y. Orlov<sup>7</sup>, C.S. Ozben<sup>11</sup>, R. Prigl<sup>5</sup>, S. Redin<sup>6</sup>, S. Rescia<sup>5</sup>, B.L. Roberts<sup>3</sup>, G. Ruoso<sup>12</sup>, T. Russo<sup>5</sup>, A.M. Sandorfi<sup>5</sup>, A. Sato<sup>16</sup>, N. Shafer-Ray<sup>15</sup>, Y. Shatunov<sup>6</sup>, Y.K. Semertzidis<sup>5,\*</sup>, A. Silenko<sup>2</sup>, E. Stephenson<sup>10,\*</sup>, R.G.E. Timmermans<sup>8</sup>, C.E. Thorn<sup>5</sup>, X. Wei<sup>5</sup>, H.W. Wilschut<sup>8</sup>, M. Yoshida<sup>16</sup>

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17. University and INFN Trieste, Italy

## *Further Reading*

F.J.M. Farley, et al., "A new method of measuring electric dipole moments in storage rings", <http://www.arxiv.org/abs/hep-ex/0307006>

Y.K. Semertzidis, et al., "A New Method for a Sensitive Deuteron EDM Experiment", <http://www.arxiv.org/abs/hep-ex/0308063>

O. Lebedev, K.A. Olive, M. Pospelov, A. Ritz, "Probing CP Violation with the Deuteron Electric Dipole Moment", <http://www.arxiv.org/abs/hep-ph/0402023>

C.-P. Liu, R.G.E. Timmermans "P- and T-odd two-nucleon interaction and the deuteron electric dipole moment", <http://www.arxiv.org/abs/nucl-th/0408060>

Collaboration home page: <http://www.bnl.gov/edm/>

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